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36  Separate items are enclosed
122 039

MEMORANDUM FOR PRS (In-House Publication)

Propulsion Science and Advanced Concepts Division

FROM: PROI (TI) (STINFO)

30 Nov 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-227**
    Miller, T. C., "Fracture Mechanics Research at Air Force Research Laboratory"

**Visit by Swedish Diplomats to AFRL**          **(Statement A)**
**(AFRL/Edwards, 05 Dec 2000)**

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# Fracture Mechanics Research at Air Force Research Laboratory

## December 5, 2000
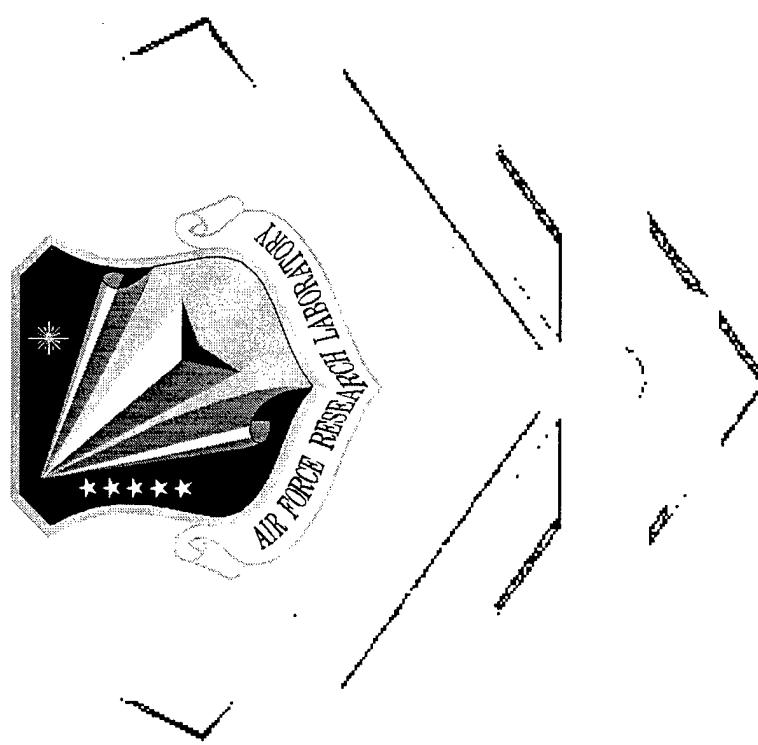
# Two Crack Failure Modes in Solid Rocket Motors

Debond
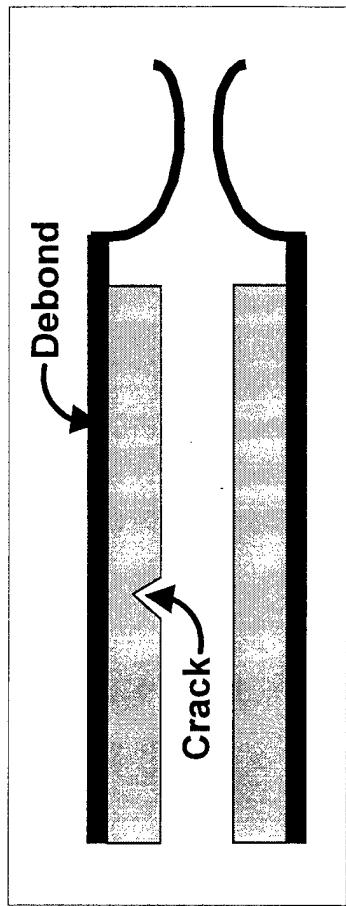
Crack

- **Does Crack Propagate Under Service Loads?**

- **If the Crack Propagates, How Does it Propagate?**

- Applied Loads
- Initial Crack Length $a_i$
- Burning Rate b

Stress Analysis

$K_I > K_{Ic}$

No → $a_i$ is not Critical

Yes → $\dfrac{da}{dt} > b$

No → a is not Critical

Yes →

Crack Growth Analysis Required

$$a_i + \sum_{j=1}^{t_f} a_j = a \text{ Critical}$$
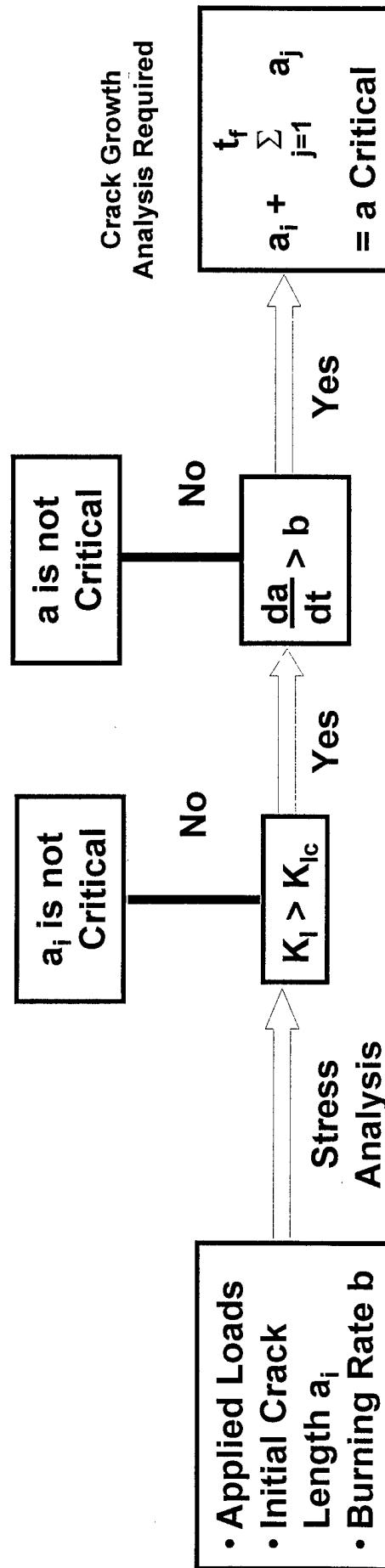
# Good Correlation Exists Between the Predicted and the Measured Crack Initiation Load and the Initial Crack Length

- Based on a Micro-Macromechanical Model and a Stress Instability Criterion, the Predicted and Measured Average Initial Crack Lengths are 1.2 mm and 1.0 mm for D = 0.25 inch Hole and 1.5 mm and 1.3 mm for D = 0.5 inch Hole.

Critical Crack
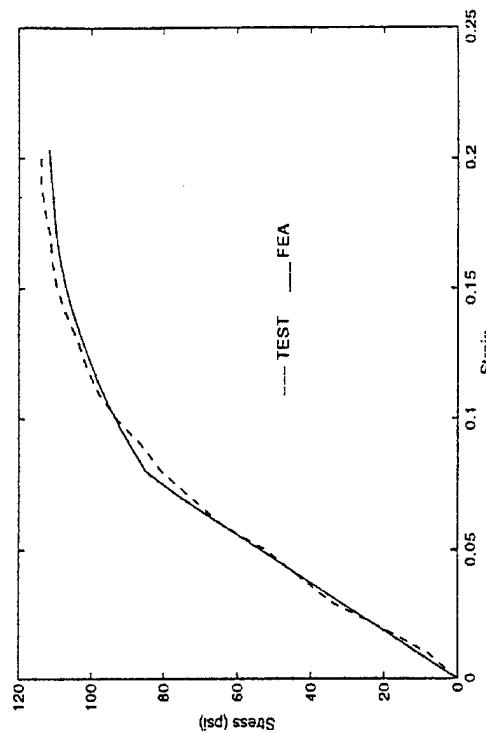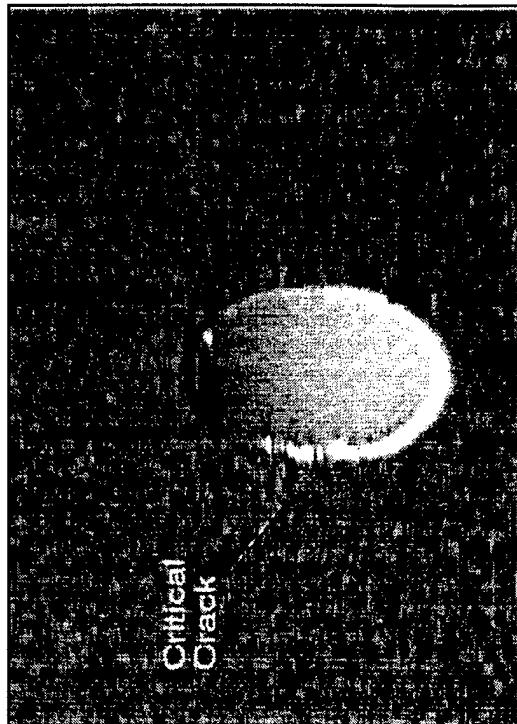


Stress-Strain Curve at Strain Rate 0.02/min
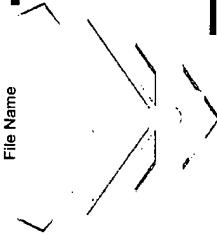
# There Exists a Representative Area for a Valid Continuum Assumption of Solid Propellant

Standard Deviation Of The I x-ray mean

Size of Region, mm

Stretch, inch
- 0.80
- 0.75
- 0.70
- 0.65
- 0.60
- 0.55
- 0.50
- 0.45
- 0.40
- 0.35
- 0.30
- 0.25
- 0.20
- 0.15
- 0.10
- 0.05
- 0.00

STD vs. Size of Region

Standard Deviation Of The Mean Strain (Micro Strain)

Size of Region, mm

- 6.21 psi
- 12.42 psi
- 18.63 psi
- 24.84 psi
- 31.05 psi

- Based on micro-measurements, the representative area is 2 mm x 2 mm.

- The existence of the representative area provides a basis for conducting stress analysis of solid rocket motors from nondestructive testing data.

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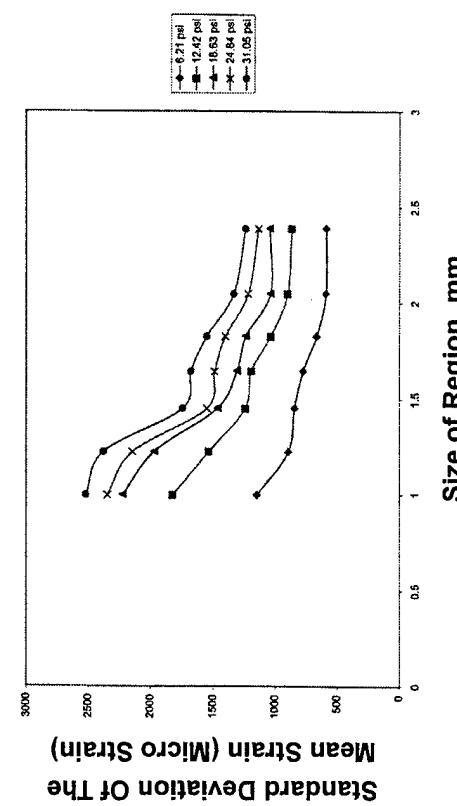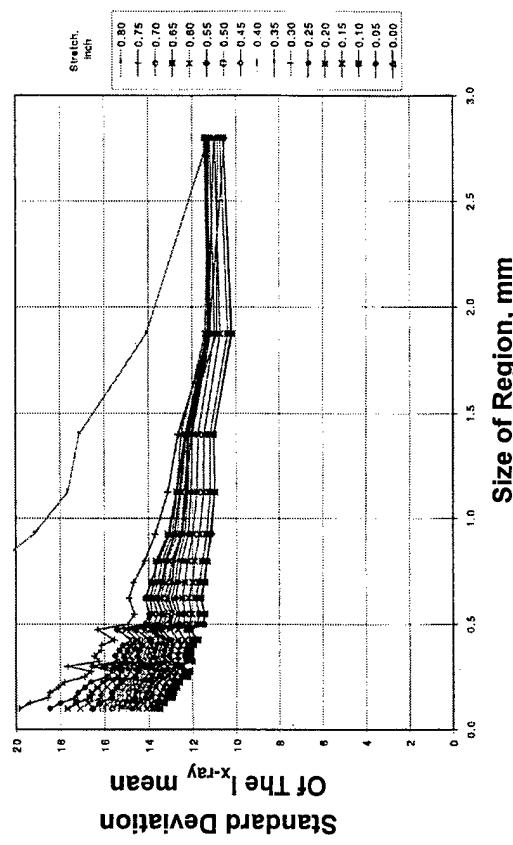
# A Technique is Developed to Predict the Initial Crack Length in Solid Propellants

- Based on fracture mechanics and fracture data, the predicted and the estimated initial crack lengths are 3.3 mm and 2.5 mm, respectively.

- The initial crack size follows the second asymptotic distribution of the maximum value.

- The determination of the statistical distribution function of the initial crack makes statistical analysis of crack growth feasible.

Crack size a in inches: 0.143, 0.141, 0.139, 0.137, 0.135, 0.133, 0.131, 0.129, 0.127, 0.125, 0.123, 0.121

Time t in minutes

$t^*$

| | $a_o$ (in.) | R |
|---|---|---|
| ◯ | 0.0 | 0.966 |
| ◇ | 0.1 | 0.958 |
| △ | 0.2 | 0.963 |
| □ | 0.3 | 0.983 |

$a_o$: 0.00 in, 0.10 in, 0.20 in, 0.30 in

$\sigma_m$, psi

Log $t_{max}$
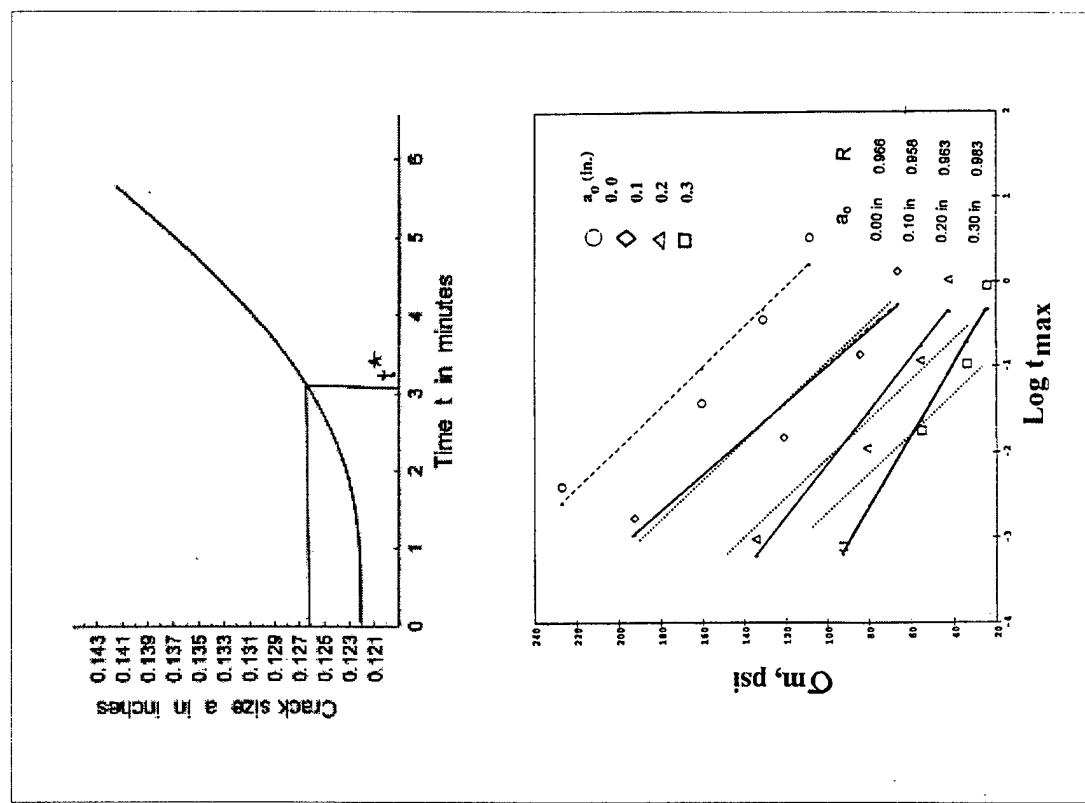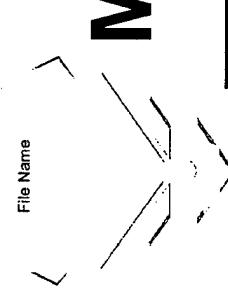
# The Inhomogeneity of Microstructure Plays a Key Role in Crack Initiation and Growth



0.475 inch

0.450 inch

0.425 inch

- Non-propagating cracks are formed in weak regions with a mean crack length of 1.5 mm

- In general, a critical crack is formed by the coalescence of small non-propagating cracks with an average critical crack length of 3.15 mm
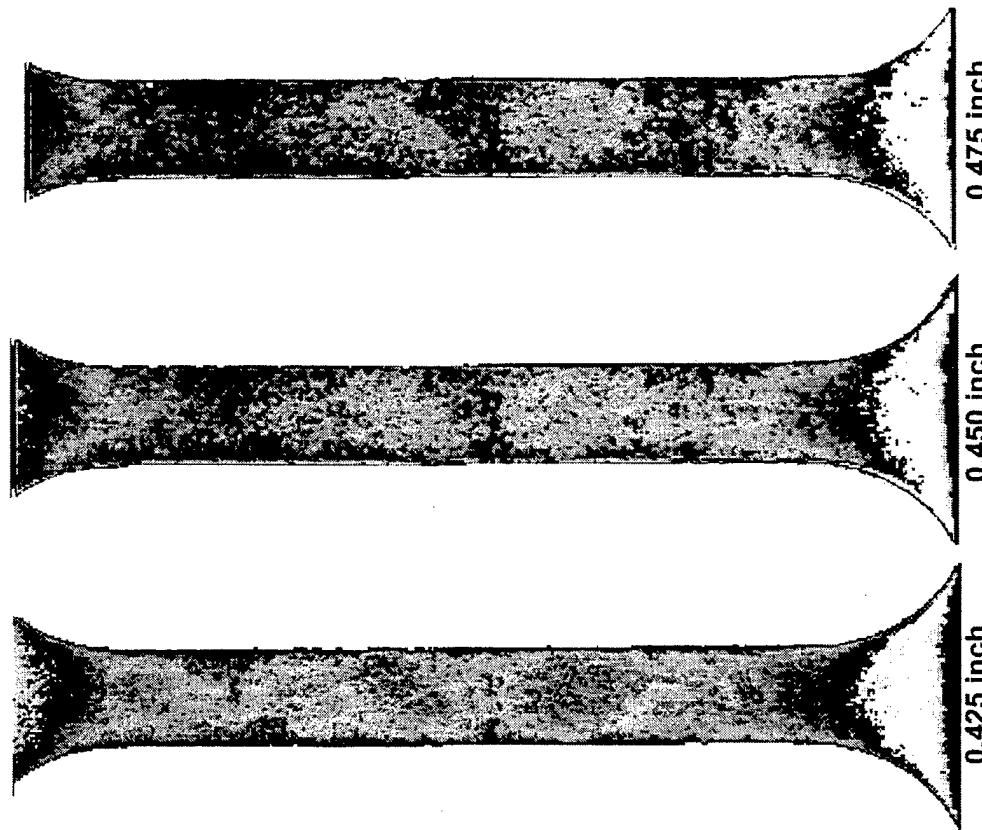
# Microstructure Induces a Large Inhomogeneous Variation in the Strain Field Near the Crack Tip



Maximum principal strain for step 5
Far Field Strain 5%



Maximum principal strain for step 2
Far Field Strain 2%
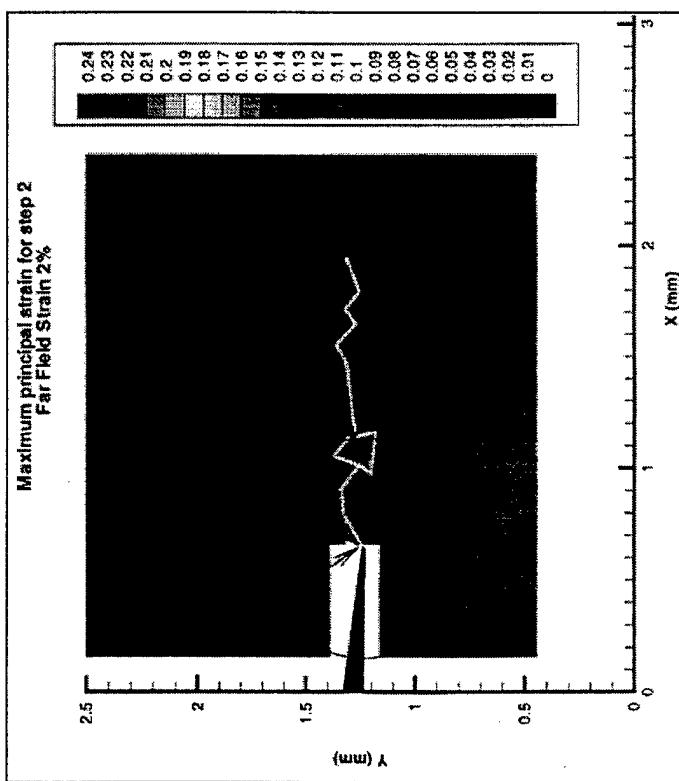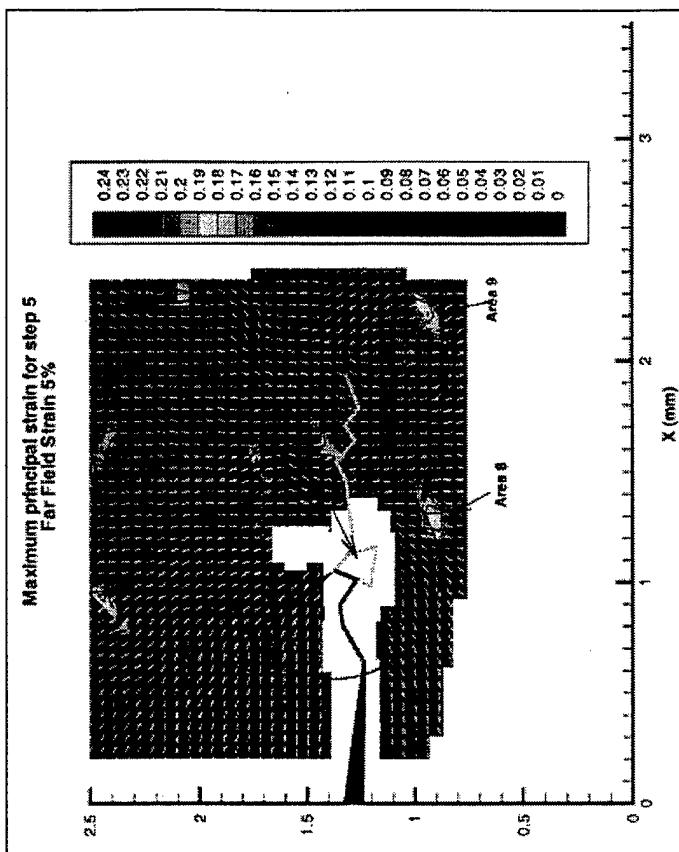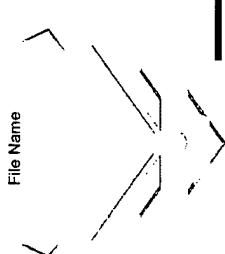
- The Interaction Between Large Deformation and Crack Propagation Process Localizes around The Crack Tip Regions
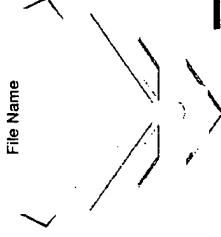
# The Predicted Crack Growth Behavior Compares Well with Experimental Observation

**Crack Length, mm**

experimental
computed
2.54 mm/min Loading Rate

time (s)

**Crack Length, mm**

experimental
computed
12.7 mm/min Loading Rate

time (s)

- The variation of the strain rate near the crack tip was included in computer simulations of crack growth.

- The realistic modeling of crack growth can be a useful tool in predicting service life of solid rocket motors
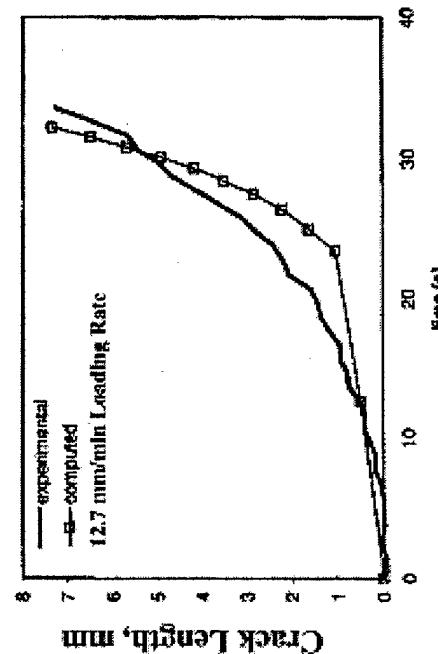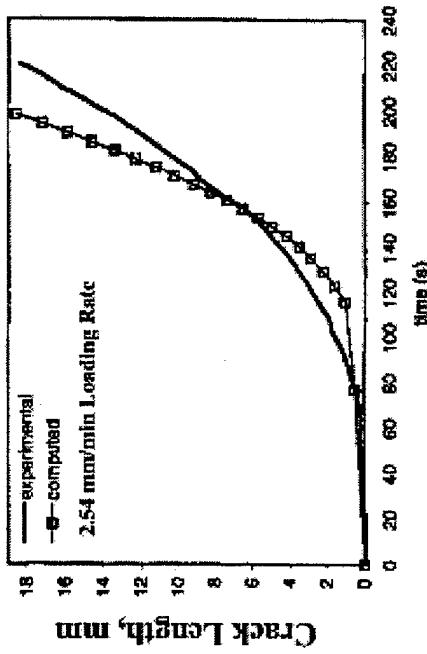
# Critical Defect Assessment (CDA) Program Introductory Information

**Objectives:**

**Enhance the capabilities of the existing service life prediction methods of the Structural/Ballistic Analysis System (SBAS) in three areas:**

– Fracture mechanics

– Coupled analyses between structural mechanics and Computational Fluid Dynamics (CFD) codes

– Automated geometric modeling of known flaws using non-destructive evaluation (NDE) data
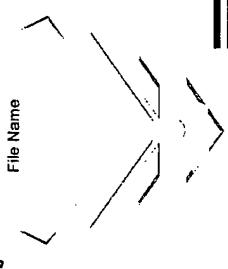
# CDA Task 1: Fracture Mechanics

**Objectives:**

Conduct exploratory development effort to enhance existing fracture mechanics models of:

- Development of the initial crack – its geometry and size (continuum failure)

- Growth initiation threshold

- Fracture growth propagation -- the direction and speed of propagation

Develop algorithms for building fracture modules into existing capabilities, such as SBAS

# CDA Task 1.1: Initial Crack Development

**Analytical Methods:**

- **Coalescence of local load-induced damage zones forms a crack**

  – Continuum failure criterion will be used to determine when local material elements will fail

  – Experimental data will show the contour of the damage zone formed by coalesced failed elements

  – The coalesced damage zone represents the initial crack

  – When possible, the micromechanics model in the SLPT program will be employed

# CDA Task 1.2: Crack Growth Initiation Threshold or Onset

## Crack Growth Initiation Threshold or Onset

- The predictive method on this subject is reasonably developed (e.g. NASA SPIP, AF S/BRAM programs)

- The analysis method is built upon a linear elastic model. Exploratory effort on using non-linear viscoelastic (NLVE) models are also being examined

- Fracture mechanics parameters, stress intensity factor (K), strain energy release rate (G), and the J-integral, are interchangeably used

- Satisfactory predictions of crack and debond growth onsets have been made (e.g. CPIA publications)

# CDA Task 1.3: Crack Growth Propagation

## Characteristic Relationship Between Crack Speed and Stress Intensity Factor "K"

FOR TYPICAL PROPELLANT

Stress intensity factor [psi√in.]

Crack speed (in/min in log scale)

Test temperature

▽ 15°F

● 30°F

□ 50°F

◁ 70°F

◇ 75°F

○ 85°F

—— Master curve

$$da/dt = \alpha\,(K - K_c)^{\beta}$$

$\alpha = 9.55 \times 10^{-9};\ \beta = 4.57;\ K_c = 1.62$

$\alpha = 6.07 \times 10^{-10};\ \beta = 5.88;\ K_c = 4.79$

low rate